

A FIVE-WATTS G-M/J-T REFRIGERATOR FOR LHe TARGET AT BNL

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ABSTRACT

A five-watts G-M/J-T refrigerator was built and installed for the high-energy physics research at Brookhaven National Laboratory in 2001. A liquid helium target of 8.25 liters was required for an experiment in the proton beam line at the Alternating Gradient Synchrotron (AGS) of BNL. The large radiation heat load towards the target requires a five-watts refrigerator at 4.2 K to support a liquid helium flask of 0.2 meter in diameter and 0.3 meter in length, which is made of Mylar film of 0.35 mm in thickness. The liquid helium flask is thermally exposed to the vacuum windows that are also made of 0.35 mm thickness Mylar film at room temperature. The refrigerator uses a two-stage Gifford-McMahon cryocooler for precooling the Joule-Thomson circuit that consists of five Linde-type heat exchangers. A mass flow rate of 0.8~1.0 grams per second at 17.7 atm is applied to the refrigerator cold box. The two-phase helium flows between the liquid target and liquid/gas separator by means of thermosyphon. The paper presents the system design as well as the test results including the control of thermal oscillation.

INTRODUCTION

Engineers at BNL have been building the cryogen targets for high-energy physics experiments for more than 35 years at Alternate Gradient Synchrotron of BNL. Hundreds of cryogen targets were built in various shape and sizes, which involved the liquid hydrogen and deuterium, liquid helium3 and helium4. The basic characteristics of these targets is its thin Mylar film flask, high thermal radiation heat load, limited vapor fraction, minimum material mass surrounding the target, fast empty and refill, remote and reliable operation, and critical safety measures.

Dewar filling [1] and cryocooler [2] are the two basic refrigeration methods applied to support the cryogen targets. The Dewar filling target is an open cycle system. It is simple and less cost in construction and has no limitation on cooling power in principle. The

disadvantages are cumbersome in operation, ensured interruption due to disturbance in cryogen transfer, and high cost of liquid helium without recovery. The cryocooler-refrigerated target is a closed cycle system. It is easy in operation and has no interruptions in principle. The disadvantages are its complexity, high cost in construction, and limitation on cooling power. Other factors concerning selection of refrigeration method at BNL are the operation time of the experiment, the availability of major equipments, and the scale of project funding. The compromise is always made between the mentioned factors above and the specification of physics experiments.

The current experiment E931 at AGS requires a liquid helium target in a volume of 8.25 liters. The system was built and installed in the proton beam line and is scheduled to run in August 2001. Because the large heat load of the target, estimated as 3 watts at 4.2K, the newly in-house design and construction of a 5 watts refrigerator was carried out at BNL. The cryocooler to support this target is not commercially available in the field. Among the cryocoolers marketed, the cooling power of a single unit of G-M cooler or pulse tube cooler is still limited in a range of 0.5~1.5 watts at liquid helium temperature. Therefore, the G-M/J-T scheme was selected to fulfill the task. The G-M/J-T cooler can provide larger refrigeration if the system uses a larger G-M cooler for precooling and uses the compressor with high mass flow rate at proper supply and suction pressures.

G-M/J-T HELIUM REFRIGERATOR

The flow diagram of the system is given in **FIGURE 1**. There are two flow circuits, the J-T forced flow circuit and the target thermosyphon flow circuit. In order to provide a

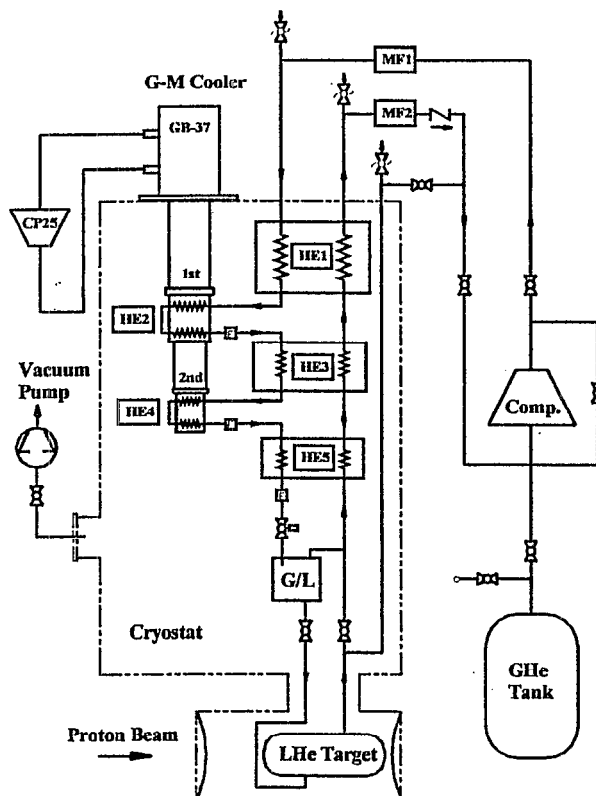


FIGURE 1. System flow diagram

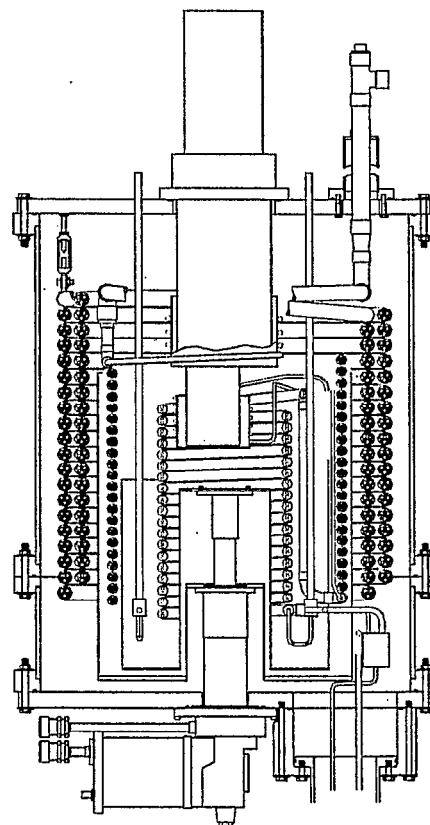


FIGURE 2. Refrigerator cold box

stable liquid helium pool in the Mylar flask, a liquid/gas separator is used between these two circuits.

In the J-T circuit, the high-pressure helium gas at 17.7 atm from compressor flows in turns through five heat exchangers, J-T valve, and separator, and then returns to the compressor at 1.2 atm. The three major heat exchangers are the Linde-type counter-flow multi-tube ones which are made of copper tubes. The two single loop heat exchangers are thermally attached to the first and second stage of the G-M cooler.

TABLE 1 shows the design parameters for each heat exchanger, which gives the bundle structure, tube size, and flow resistances both in high pressure and low pressure loops in each heat exchanger. FIGURE 2 shows the arrangement of the G-M cooler and the heat exchangers in the cold box. The Cryomech GB-37 cold-head with CP25 compressor was selected because of its large capacity both at the first and the second stages. The J-T valve is adjustable from the top flange of the cryostat.

In the target thermosyphon circuit, liquid helium is supplied from the bottom of the separator to the bottom of the target and vapor returns from the top of the target to the top of the separator. Two cryo-valves are used in the circuit to isolate the Mylar flask from J-T circuit for system cool-down. A helium gas tank in volume of 3.7 cubic meters is used to complete the closed system, which allows entire operation goes from warm start-up to normal cold run with full target without adding gas. This also provides a measure of helium condensing rate and liquid level in the Mylar target. The tank pressure and target temperatures are measured for system control.

LIQUID HELIUM TARGET

The liquid helium target has a volume of 8.25 liters. It is a cylinder with elliptical end-caps, shown in FIGURE 3. The diameter of flask is 0.2 meter and the length is 0.3 meter. The flask is made of Mylar film of 0.35 mm in thickness. In order to reduce the materials around the target as much as possible for the physics measurement in particle counters, the aluminum vacuum cylindrical chamber of 1.6 mm in wall thickness and 254 mm in diameter is used. At up-stream and down-stream of the chamber are the Mylar vacuum windows, which are also made of Mylar film of 0.35 mm in thickness. The 30-40 layers of superinsulation are applied to cover the liquid flask. There is no heat shield used between the liquid helium flask and the vacuum chamber at room temperature. The helium supply and return lines for the target are looped into the cold box to the liquid/gas separator through the two cryo-valves. The target transfer lines contain two special cryogenic fittings that provide convenient connections between the two circuits.

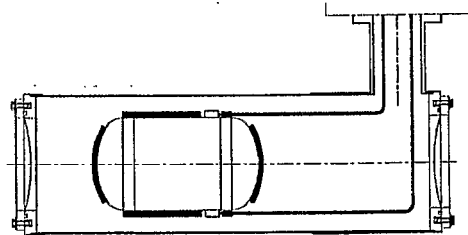


FIGURE 3. Mylar target flask with Mylar vacuum windows.

TABLE 1. Design parameters for each heat exchanger

Heat Exchanger	HE-1	HE-2	HE-3	HE-4	HE-5
Tube Size at HP (No / ID / L)	3/ 4.8mm/ 54m	1/ 6.3mm / 2m	3/ 3.2mm/ 24m	1/ 3.2mm / 2m	2/ 3.2mm /12m
Tube Size at LP (No / ID / L)	1/20mm/54m		1/ 14mm / 24m		1/ 11mm/12m
Flow Resistance (HP / LP)	15.9kPa/10kPa	0.44kPa	8.5kPa/5.3kPa	1.1kPa	1.4kPa/1.5kPa

HEAT LOAD VS. REFRIGERATION

The heat load at the target flask itself is 1.85 watts, which is contributed by thermal radiation through the superinsulation layers from the surfaces of vacuum chamber at room temperature. This was verified by the evaporating rate of liquid in the flask at steady warming-up when the target was isolated from the J-T flow circuit, which was 2.8 L/hr. The heat conduction through the two cryo-valve stems introduces 0.4 watts to the target flow circuit. And a large pressure relief line for the target introduces 0.1 watts by heat conduction. Heat load to the liquid/gas separator and transfer lines presents 0.65 watts. The total heat load at 4.5 K was 3 watts.

The performance of the refrigerator was analyzed using a numerical package of Aspen. **FIGURE 4** gives predicted system refrigeration vs. the mass flow rates. The cooling capacity of the Cryomech GB-37 cryocooler was assumed in the analysis. The GB-37 experimental cooling-curve is given in **FIGURE 5**. The maximum refrigeration in the J-T circuit was obtained at a mass flow rate of 1.0 g/s under the same pressure differential. Since the system was not designed for commercial purposes, the sizes of heat exchangers in cold box were not the concern. The maximum refrigeration is dominated by the cooling capacities at each stage of the G-M cooler, which provides the precooling of the J-T circuit. The refrigeration from the G-M/J-T circuit was tested at different mass flow rates. For example, when the mass flow rate was 0.85 g/s at supply pressure of 17.7 atm and return pressure of 1.28 atm, the cooling capacity was 4 watts. The corresponding condensing rate in the target was 0.45 L/hr.

TARGET OPERATION

The target system is operated under the programmable logic controller. The J-T valve and the automated by-pass valve across the compressor control the mass flow rate of the J-T circuit. To protect the Mylar flask from over-pressurized during system cool-down, the target is isolated from the J-T circuit by closing the two cryo-valves to allow the large mass flow rate through the heat exchangers. Once the J-T circuit is cold, precooling of the target is provided through a by-pass loop that sends the warm gas directly to the compressor to avoid disturbing the J-T flow in the heat exchangers. When the target is cold and two isolation cryo-valves are fully open, the thermosyphon flow is established. The cool-down of the whole system took about 14 hours. It took another 18 hours to fill up the target flask. In the process of liquid target empty and refill, it took 3.5 hours to empty the full target. The normal operation is automated and non-manned.

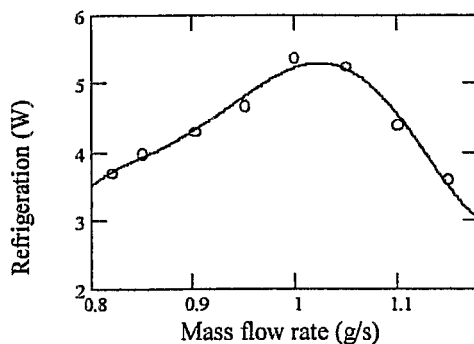


FIGURE 4. System refrigeration vs. mass flow rate of J-T circuit.

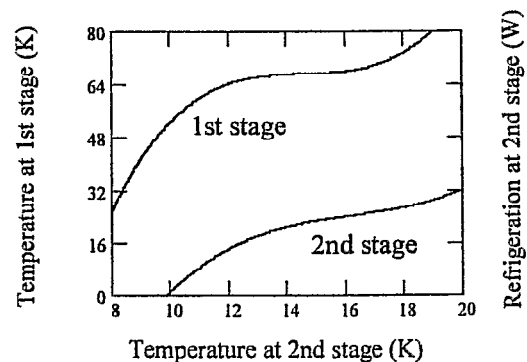


FIGURE 5. Cooling capacity of G-M cooler, at 60 W of the 1st stage.

TEST RESULTS

To evaluate the performance of the refrigerator, the temperatures were measured at inlets and outlets of each heat exchanger, at the J-T valve, and at the supply and return ports of the target. The pressures were measured in the Mylar target flask, in the gas supply and return sides of the cold box, and in helium gas tank. The mass flow rate was measured at supply and return sides of the compressor. The tested data in helium P-T diagrams at the bottom and top of the Mylar flask and the liquid/gas separator during the cool down and condensing period are shown in **FIGURE 6** and **7**, respectively. The line in the figures represents the saturation line of helium, and the circles are the test data. The heat load locally at the top and bottom of the target caused the temperature offsets in **FIGURE 6**.

THERMAL OSCILLATION AND CONTROL

The thermal oscillation in the target circuit was observed at certain conditions during the tests. The typical pattern of its kind is given in **FIGURE 8** and **9**. The similar phenomena have been observed in other target systems operated in the field. The temperatures at the supply and return lines of the target can vary at very large amplitude above the critical temperature. The pressure oscillation in the target could severely disturb the liquid helium pool in the target. Sometimes it causes the entire system to oscillate.

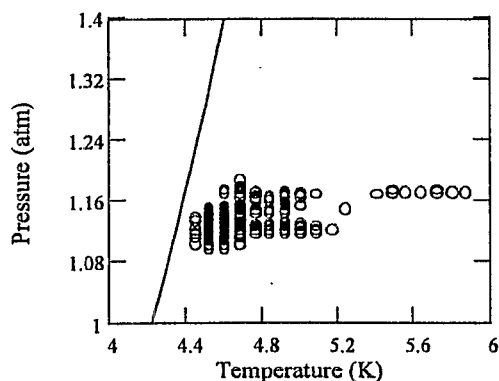


FIGURE 6a. He P-T diagram in target at bottom.

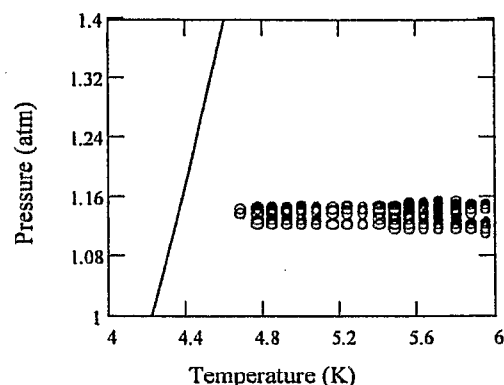


FIGURE 6b. He P-T diagram in target at top.

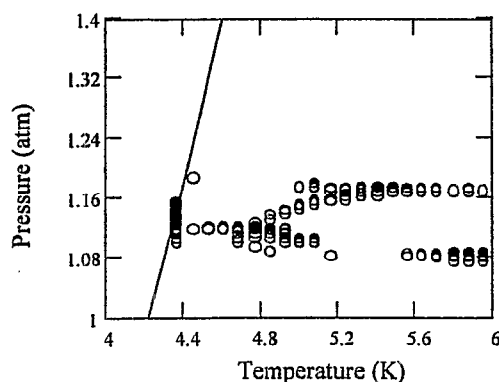


FIGURE 7a. He P-T diagram in separator at bottom.

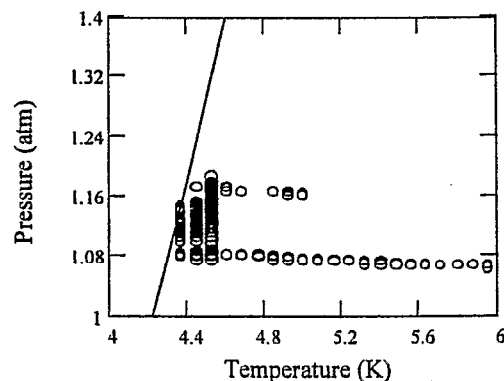


FIGURE 7b. He P-T diagram in separator at top.

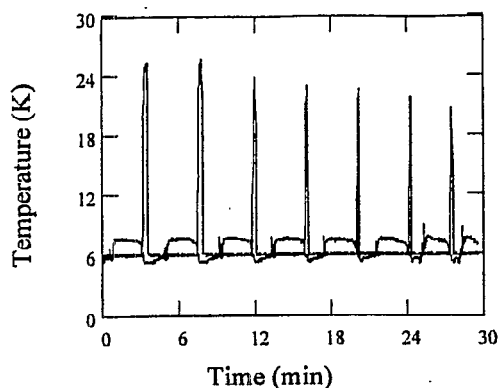


FIGURE 8. Temperature oscillation due to reduced refrigeration.

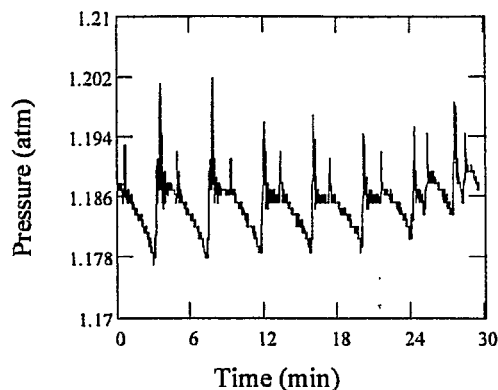


FIGURE 9. Pressure oscillation due to reduced refrigeration.

The instability of the fluid in the target presents a serious problem to the physics. Most of the times, it is due to the large heat load at the Mylar target and it is also the nature of the long transfer lines in the thermosyphon driven flows. It is almost certain to happen when the refrigeration is too close to match the heat load of the target. The system instability caused by this kind of oscillation could stop the cooling of the target even the refrigeration is slightly higher than the heat load. To eliminate the oscillation, the transfer lines in the thermosyphon circuit should avoid any adverse loops. The undersized transfer lines should also be avoided. Any thermal short such as those exists in the short-stem cryo-valves and relief valves should be avoided or properly cold-intercepted.

CONCLUSION

A five-watts G-M/J-T refrigerator was built to refrigerate a large liquid helium target for the physics experiment at BNL. The large G-M cooler such as the Cryomech GB37 was capable to serve the purpose of precooling the J-T circuit. The corresponding mass flow rate for the maximum refrigeration of the system is 1.0 g/s under the same pressure differential. This refrigerator was tested successfully to support a liquid helium target of 8.25 liters in severe thermal radiation environment. The target system was installed in the proton beam line at the Alternating Gradient Synchrotron of Brookhaven National Laboratory in May 2001 and is scheduled to take the particle beams in August of this year.

ACKNOWLEDGEMENT

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REFERENCES

1. Jia, L. X., et al, "Safety Design, Operation, and Control of a Liquid Hydrogen Target at BNL", in *Advances in Cryogenic Engineering* 43A, New York, 1998, pp. 629-636.
2. Jia, L. X., *E931 LHe Target Design Manual*, Brookhaven National Laboratory, 1999.